NBS TECHNICAL NOTE 824

A Laboratory Study of Some Performance Characteristics of an Aluminum Oxide Humidity Sensor

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A Laboratory Study of Some Performance Characteristics of an Aluminum Oxide Humidity Sensor

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A laboratory study was made of the performance of aluminum oxide humidity sensors over a range of ambient temperatures from +20°C to -60°C encompassing dew points from +18°C to frost points of -100°C. Information was obtained on such characteristics as sensitivity, hysteresis, temperature effect, pressure-altitude effect and short-term and long-term repeatability. The sensors were found to be capable of detecting frost points as low as -100°C at ambient temperatures of -40°C and -60°C. It is estimated that the total uncertainty inherent in these sensors is approximately 4°C.

Key words: Aluminum oxide sensor; humidity; humidity sensor; hygrometer; measurement of frost points; moisture measurement; water vapor measurement.

1. Introduction

The Department of Transportation's Climatic Impact Assessment Program (CIAP) [1,2,3]** includes a global study of the nature of the stratosphere. The present distributions of temperature, constituents, motions, and circulations are being actively investigated. Among the constituents that are of concern is water vapor. Measurements of water vapor concentration in the stratosphere are or will be made with instrumentation carried aloft in balloon-borne radiosondes and in high-altitude aircraft.

The National Bureau of Standards was asked to select and study the performance characteristics of several humidity sensors for possible use in CIAP. The choice of sensors for this laboratory investigation was constrained by the following considerations. First, the sensors were required to be immediately available from commercial sources, or, at least, to have progressed to a stage of development that could make them available soon. Second, they could not exceed a cost of $350 per unit. Third, they were required to be compatible with the telemetry circuitry of the radiosonde. Fourth, they were required to have a dynamic range of three orders of magnitude in measuring humidity. Fifth, they were required to have an accuracy of about 10 percent. Sixth, they were required to have a capability of detecting moisture levels equivalent to frost points as low as -90°C. Seventh, they were required to have stable calibration curves. Finally, they were required to have a known temperature coefficient.

A survey of the field disclosed two sensors that met the criteria of immediate availability and cost and showed promise for use in the radiosonde. These were: (1) the aluminum oxide sensor and (2) the miniature crystal array. In addition this survey disclosed that there were three sensors which fell into the category of limited availability or which required further development. These were: (1) the expendable dew-point hygrometer; (2) the coated piezoelectric quartz crystal; and (3) the diffusion coulometric cell. There appeared to be no other device or sensor suitable for stratospheric moisture measurements which met the specified constraints and performance requirements, at least none that did not require extensive research and development. An evaluation program was designed to yield the following performance characteristics: sensitivity, range, hysteresis, temperature effect, pressure-altitude effect, short-term repeatability, and long-term repeatability. The tests were chosen to cover the following range of parameters: (1) ambient temperatures from 20 to -60°C; (2) dew-point temperature from 18°C to frost-point temperature of -100°C; and (3) ambient pressure-altitudes corresponding to sea level and 20 km.

The purpose of this paper is to report on the results of a laboratory investigation of two forms of the aluminum oxide humidity sensor.

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** Figures in brackets indicate the literature references at the end of this paper.

TWO-PRESSURE HUMIDITY GENERATOR

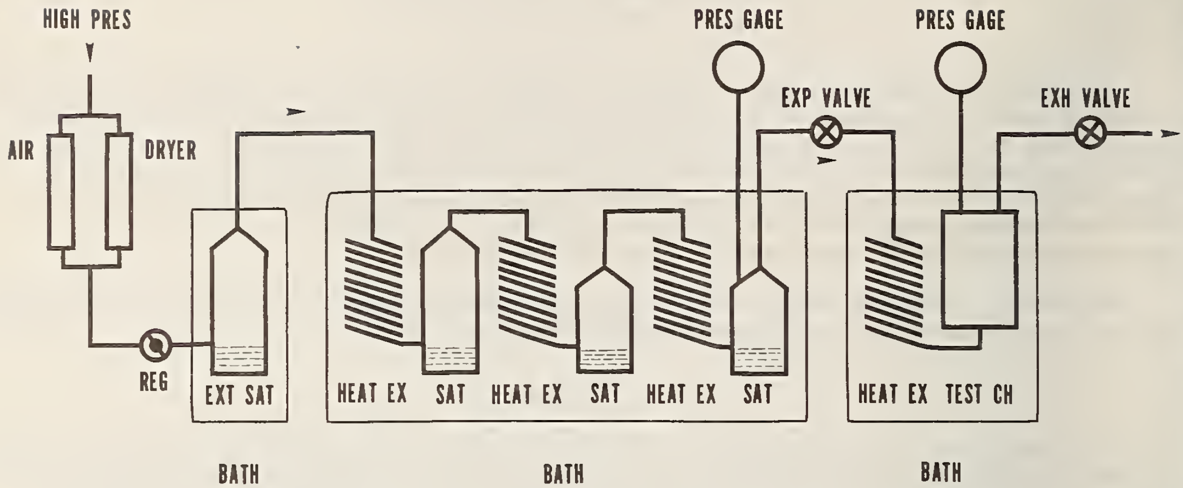


Fig. 1 Simplified flow diagram of NBS two-pressure humidity generator.

LOW FROST-POINT HUMIDITY GENERATOR

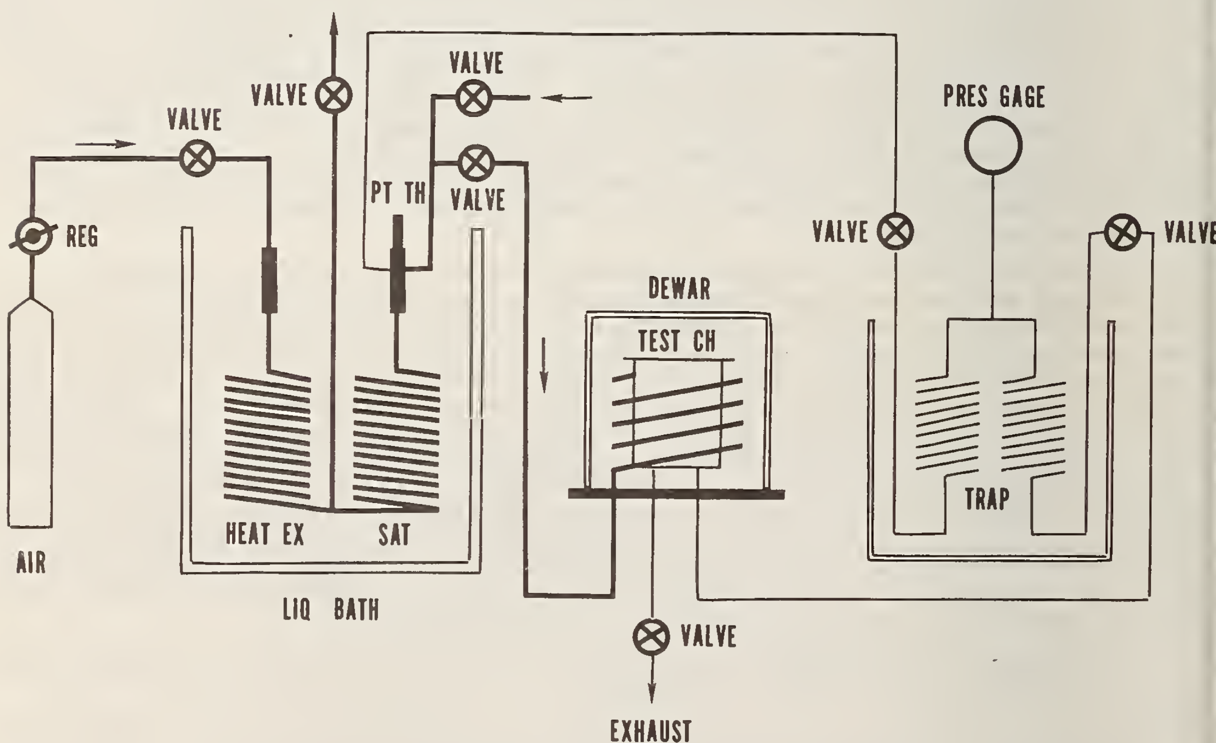


Fig. 2 Simplified flow diagram of NBS low frost-point humidity generator.

2. Description of Sensor

The aluminum oxide sensor is a variable impedance device. It consists essentially of an aluminum base or substrate with an anodized surface on top of which is a thin film of gold. The gold and aluminum serve as electrodes. Water vapor diffuses through the gold film to the oxide surface. On sorbing water vapor the oxide changes its impedance. This impedance is measured with appropriate ac circuitry.

The origin of this sensor can be traced back to the U. S. patent issued to L. R. Koller [4]. It was brought into prominence by Ansbacher and Jason [5], Jason and Wood [6], Underwood and Houslip [7], Cutting et al. [8,9], MacDowall et al. [10], Booker and Wood [11], and Jason [12]. There was further study and development work on various versions of this device by Stover [13,14], Chleck and Brousaides [15], Miyata and Watari [16], Chleck [17], Morrissey and Brousaides [18], Lai and Hidy [19], Brousaides [20], Sze [21], DelPico [22] and commercial production both in the U. S. and Great Britian.

Two forms of a commercially available sensor were used in this investigation. One was a regular or standard industrial type that has been in production for some time. The other was an experimental type which differed from the first in several fabrication details, primarily in the method of attaching electrical leads to the electrodes.

The impedance of the sensor was measured with an ac circuit which yielded a variable low-frequency output. This circuit is similar in most respects to the one used on the radiosonde. However, the latter is limited to an output of 0 to 200 hertz whereas this one can yield higher output frequencies. An electronic counter with an overall accuracy of better than 3 parts in 10^4 was used to measure the frequency.

3. Test Procedure

The National Bureau of Standards has two humidity generators which provide a capability for testing and calibrating humidity sensors and hygrometers with high accuracy. Because these generators are discussed elsewhere in great detail by Wexler and Daniels [23], Hasegawa et al. [24], Wexler [25], and Greenspan [26], only a brief description will be given here.

The NBS two-pressure humidity generator is an apparatus which produces atmospheres of known humidity. Fig. 1 is a simplified flow diagram which illustrates the principle of operation and shows the basic components. Air from a high pressure source is cleaned and dehumidified in a heatless dryer and passed through an external saturator that is temperature-controlled at 10 to 15 deg C above the desired saturation temperature. The air picks up water vapor in excess of that necessary for saturation at the desired saturation temperature. It then flows through a series of three saturators with interconnecting heat exchangers that are immersed in a temperature-controlled liquid bath. Excess water is condensed out. The gas leaves the final saturator completely saturated with vapor in equilibrium with either the liquid or solid phase (depending on the temperature) of distilled water at some fixed pressure and temperature. It now flows through an expansion valve and then into a test chamber which is located in a separate temperature-controlled bath. The pressure in the test chamber is nominally at atmospheric pressure. Measurements of the temperatures and pressures in the final saturator and in the test chamber serve to establish the moisture content of the air with high accuracy.

This apparatus is capable of generating humidities as low as -70°C in frost point. A range of ambient temperatures from +60 to -55°C can be achieved in the test chamber. The flow rate through the apparatus is maintained at 0.0014 m^3/s (84 lpm). This is equivalent to a mean air speed of about 0.02 m/s through the test chamber. The uncertainty in frost point, over most of the operating range, does not exceed 0.1 deg C.

The NBS low frost-point humidity generator also produces atmospheres of known humidity. Fig. 2 is a flow diagram which illustrates its principle of operation. Clean dry air enters a heat exchanger immersed in a liquid bath and is brought to a desired fixed temperature. It then passes through a saturator, a long helical coil of stainless steel tubing, the interior of which is coated with a thin film of ice. The path is sufficiently long so that emerging from this coil the air is completely saturated with respect to ice at the temperature of the surrounding bath. The air then flows into a gold-plated test chamber which is separately temperature-controlled. A small correction is made for the slight difference in absolute pressure between the saturator and the test chamber. The frost point produced by

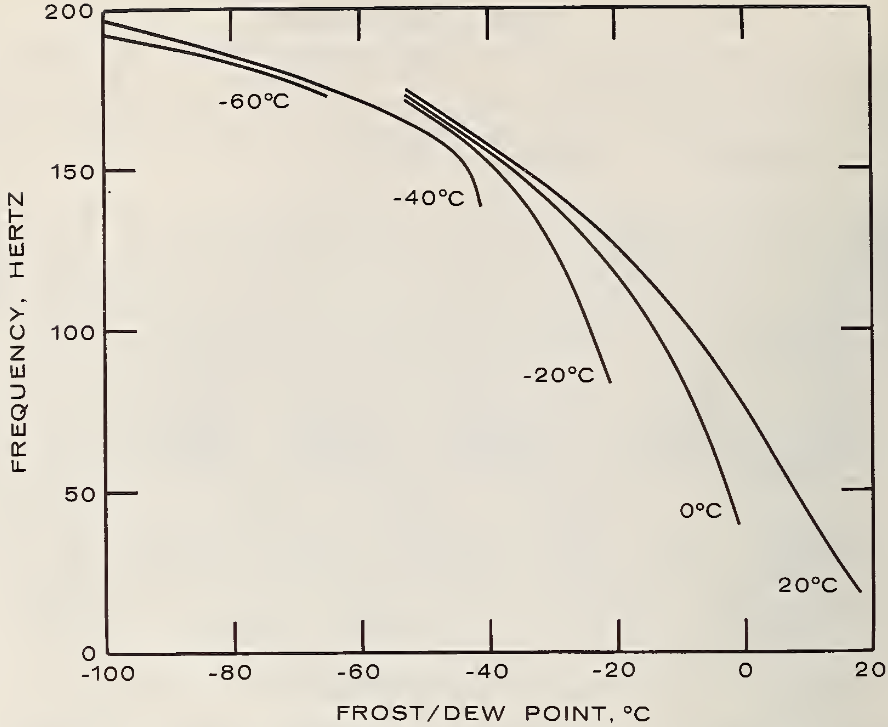


Fig. 3 Family of calibration curves (isotherms) for a typical standard sensor.

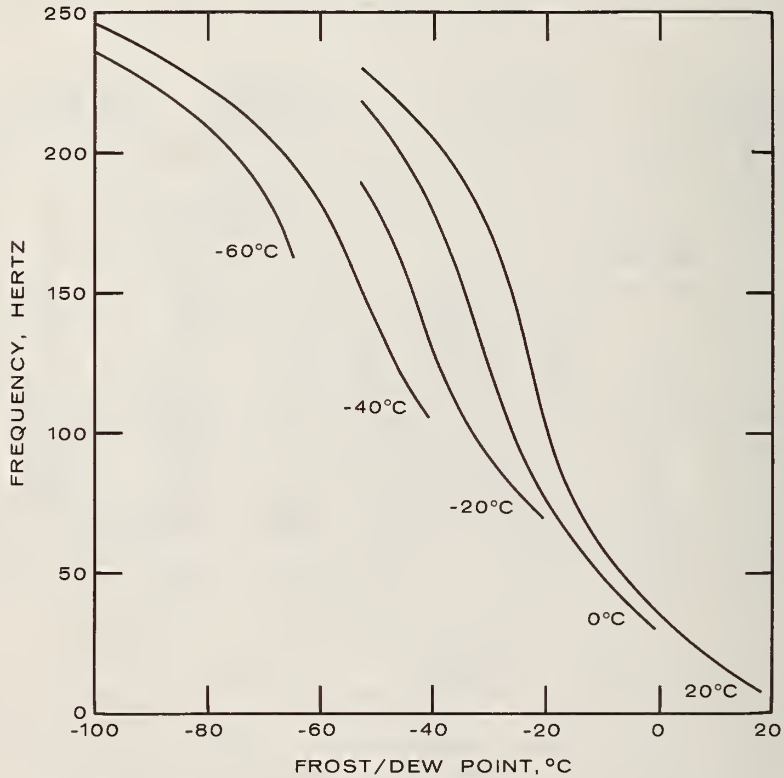


Fig. 4 Family of calibration curves (isotherms) for a typical experimental sensor.

this apparatus is basically equal to the temperature of the saturator and is measured with a platinum resistance thermometer. With this apparatus frost points from -30 to -100°C can be generated in atmospheric air and other gases. The test chamber can be operated at ambient temperatures from +25 to -100°C. Ambient pressures from atmospheric pressure to 500 Pa (5 mb) can be established within the system. The flow rate is maintained at 3.3×10^{-5} m^3/s (2 lpm). This is equivalent to a mean air speed of about 1.7×10^{-3} m/s through the test chamber. The uncertainty in frost point does not exceed 0.2 deg C.

The procedure followed in this work was to use the two-pressure humidity generator for tests at ambient temperatures from +20 through -40°C and to use the low frost-point generator at ambient temperatures of -40 and -60°C. At -40°C the operating ranges of the two generators were chosen so as to produce an overlap in the test humidities.

Ten sensors were tested simultaneously, five of the conventional industrial type and five of the modified experimental type. These ten sensors were selected by the manufacturer for use in these tests.

At each ambient temperature, a reasonable number of humidities was chosen to cover the desired test range. At each ambient temperature, the highest frost or dew point to which the sensors were subjected was chosen so that the equivalent relative humidity did not exceed 90 percent. This upper limit was set to preclude the possibility that humidities close to saturation might adversely affect the performance of the sensors. Except at the -60°C ambient temperature each test range encompassed two or more contiguous smaller spans. The ranges and spans are shown in Table 1. Within each span the sensors were cycled one or more times from the lowest to the highest frost point and then back to the initial point, except for the -55 to -100°C frost point span at the -40°C ambient temperature and the -65 to -100°C frost point span at the -60°C ambient temperature. For these latter two spans, the humidity change was made only in one direction, from the lowest to the highest frost point. In each span the sensors were exposed successively to three or more different constant humidities. After each test humidity was established readings were taken periodically until no further significant change was observed. In the two-pressure humidity generator the exposure times to reach steady state conditions at ambient temperatures of +20, 0, -20 and -40°C were 30, 40, 60 and 120 minutes, respectively. In the low frost-point humidity generator, the comparable steady state exposure times varied from 1 day to 9 days at frost points of -55 to -100°C. In changing from one test humidity to another, the sensor exhibited an initial fast response and then a slow drift to its final reading.

Response times or lags should not be inferred from these observations of exposure times. No attempt was made to differentiate between the generator and the sensor lag. Furthermore, such parameters as air velocity and sensor orientation were different in the two generators. The essential criterion governing the exposure time was the allowance of adequate time for the system (sensors and test chamber) to equilibrate after each change in humidity.

Each sensor was electrically connected to the measuring circuit through its individual shielded 2-conductor cable and a selector switch. It was noted that the output reading was affected by the length of cable, the relative positions of the separate cables, laboratory location, and stray capacitances. By keeping the circuit, cables, and surroundings in each humidity generator fixed and stable, the disturbances to the readings were minimized. Under these conditions satisfactory repeatability was obtained. Individual capacitance calibrations were made of the measuring circuit and the specific cable used with each element in each generator. These calibrations were used to adjust the output readings taken with the low frost-point generator to compensate for differences arising from the two test set-ups. The oscillator was operated only while measurements were being taken. Between measurements there was no excitation of any element.

Two sets of calibration runs were made at atmospheric pressure. The first set included the entire ensemble temperatures and spans listed in Table 1. This set comprises the initial runs. The second set was limited to ambient temperatures of 20 and -40°C. At 20°C the same four spans were used whereas at -40°C only the -41 to -53°C and -56 to -68°C frost point spans were used. This second set comprises the final runs and was made five months after the first set. After the initial runs were completed, and prior to the start of the final runs, the ten elements were calibrated at an ambient pressure of 5000 Pa (50 mb), and ambient temperature of -40°C, and over a frost-point range of -55 to -90°C at successively lower frost-point temperatures.

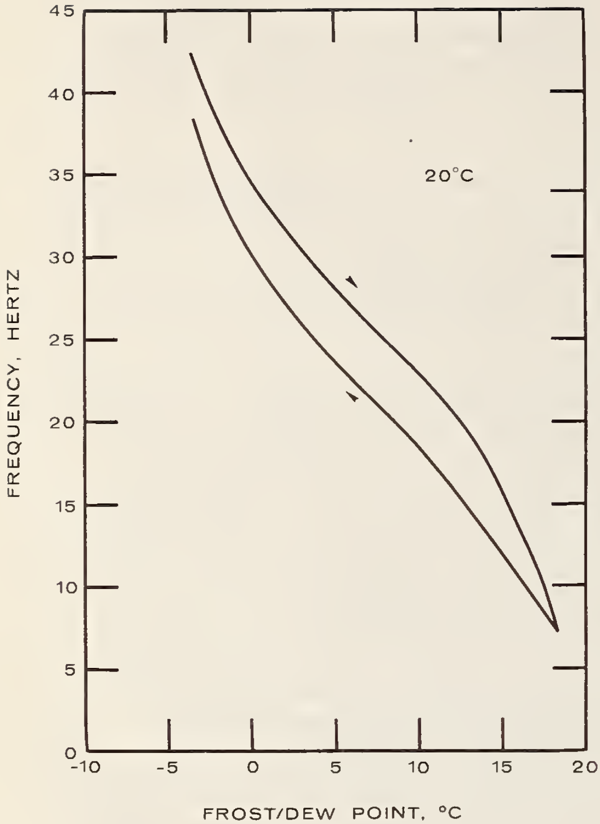
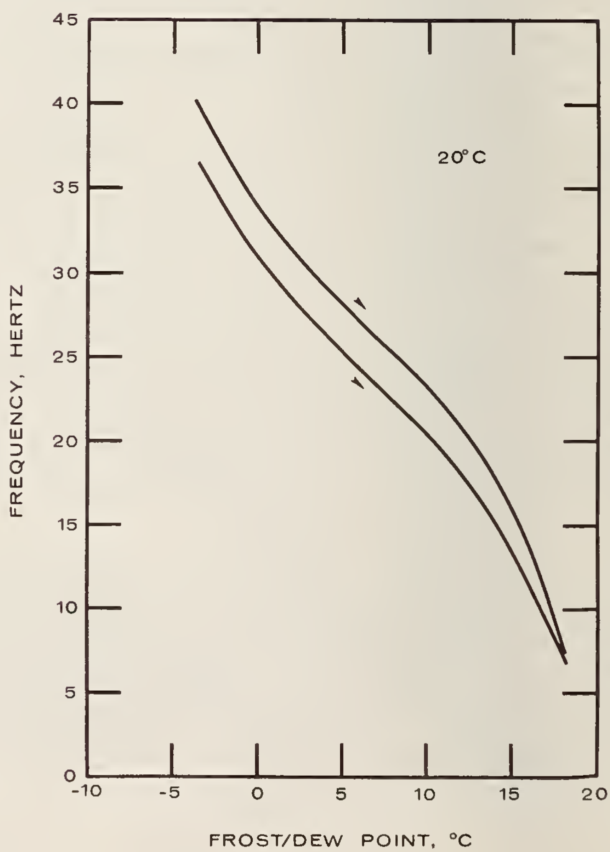


Fig. 5 Typical rested state hysteresis loop at +20°C for a span from a frost point of about -4°C to a dew point of about +18°C. The arrows indicate the direction of the humidity change.

Fig. 6 Short term repeatability. Typical plot of two calibration curves at an ambient temperature of +20°C obtained on two successive days on the same sensor.



4. Results

A family of calibration curves is shown in Figure 3 for a typical standard or conventional type of sensor and in Figure 4 for a typical experimental type of sensor. The output in hertz has been plotted as a function of frost point (below 0°C) and dew point (above 0°C) for ambient temperatures of 20, 0, -20, -40 and -60°C. For purposes of this paper, the term "frost point" will be used to refer to frost points below 0°C and to dew points above 0°C. The output frequency increases with decreasing frost point. There is a displacement of each isotherm to the left with decreasing ambient temperature. Therefore, for any given output frequency, the corresponding frost point is a function of ambient temperature. At ambient temperatures of -40 and -60°C, the sensor has sensitivity to detect humidities with equivalent frost points as low as -100°C. No attempt was made to test the sensor at frost points below -53°C at the higher ambient temperatures.

There is a tendency for the calibration curves of the standard type sensor to merge at the higher output frequencies and to diverge at the lower output frequencies. The reverse behavior occurs with the experimental type. The temperature coefficients are given in Table 2. These express the change in frost-point temperature per deg change in ambient temperature for fixed frequencies. They indicate the horizontal spread among the isotherms at a given output frequency. They can be used to estimate the error in indicated frost point due to an uncertainty in, or a failure to account for, the ambient temperature. The temperature coefficients tend to be larger for the experimental type of sensor.

The sensitivity of the sensor is shown in Table 3. An average sensitivity was calculated for each element by dividing the overall change in measured output frequency by the corresponding change in frost point for each ambient temperature. These sensitivities were pooled for each ambient temperature to yield mean values. The five mean values for each type were then combined to give a composite mean of 1.8 Hz/deg C frost point for the standard type and 3.2 Hz/deg C frost point for the experimental type. The -20°C isotherm exhibits the greatest sensitivity whereas the -60°C isotherm shows the least. The composite mean sensitivity of the experimental type is almost twice that of the standard type. For the -40°C and -60°C isotherms the ratio of sensitivities is 2.4 and 3.7.

A typical hysteresis loop for a span extending from a frost point of about -4°C to a dew point of +18°C at an ambient temperature of +20°C is shown in Figure 5. This loop was obtained without prior humidity cycling over the +18 to -4°C dew or frost point span at ambient temperature of 20°C. This first test loop will be referred to as the "first calibration cycle" obtained for the sensor for the particular dew or frost point testing span. For any output frequency the difference in frost points between the increasing and decreasing humidity branches of the loop is defined as the hysteresis. The average of the differences in frost points for equally spaced frequencies is called the average hysteresis; the maximum difference for the entire loop is the maximum hysteresis for the span. A summary of the average and maximum first calibration cycle hysteresis for each element for various temperatures and spans is given in Tables 4 and 5 respectively.

There appears to be no significant difference in hysteresis between the standard and experimental types of sensor. At each ambient temperature the hysteresis is substantially larger for the span enclosing the higher humidities (frost points) than for the spans enclosing the lower humidities. Furthermore, the hysteresis is larger at the higher ambient temperatures.

Figure 6 is a typical plot of two calibration curves covering a frost or dew point span of -4 to +18°C at an ambient temperature of 20°C. Only the increasing humidity branches of the hysteresis loops are shown. These two curves were obtained on the same sensor on successive days. Therefore, the displacement may be taken as an indication of the short term repeatability of the sensor. Shifts of this kind occur to a greater or lesser extent with each element. This short term repeatability varies with ambient temperature and span. Average and maximum values of short term repeatability are given in Tables 6 and 7. Again, there appears to be no significant difference in behavior between the two types of sensor. As in the case for hysteresis, at each ambient temperature the short term repeatability (more precisely, the lack of repeatability) is larger for the higher humidity spans than for the lowers ones; also, the shifts are larger at the higher ambient temperatures.

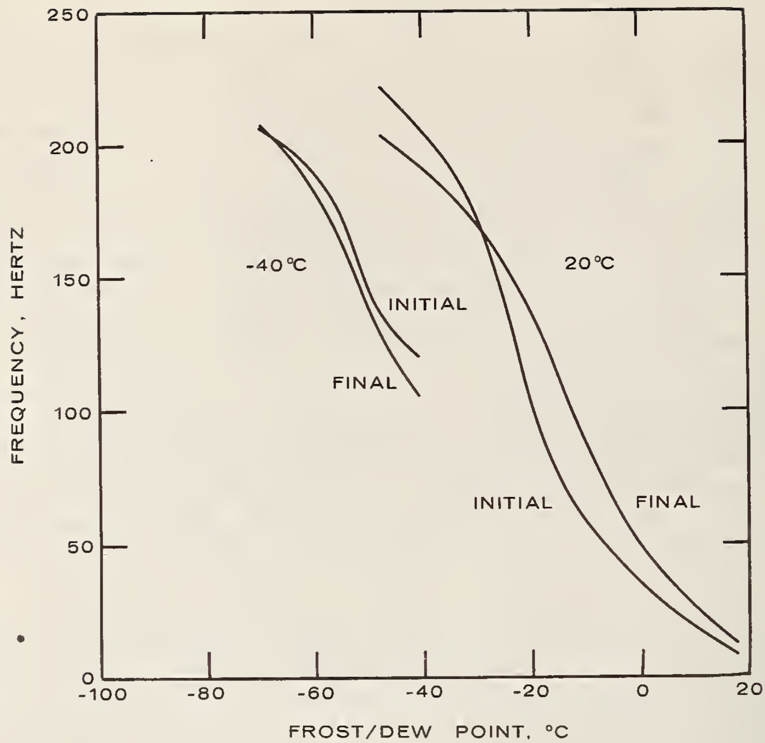


Fig. 7 Long term repeatability. Typical plot of +20 and -40°C isotherms. The "final" curves were obtained 5 months after the "initial" curves

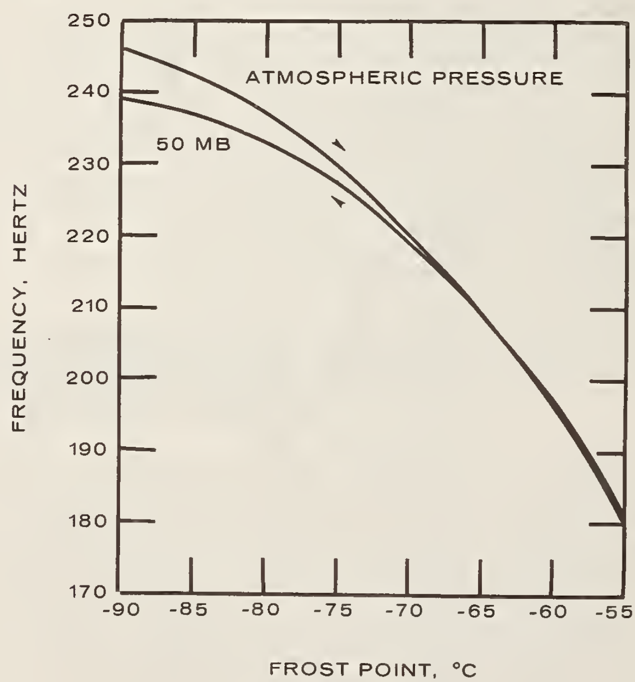


Fig. 8 Ambient pressure effect. Typical plot of -40°C isotherm obtained at standard atmospheric pressure and at 5000 Pa (50 mb). Divergence of the curves may not be significant.

Figure 7 is a typical plot of 20 and -40°C isotherms based on calibration runs made about 5 months apart. Only the increasing humidity branches of the hysteresis loops are shown. During the interval between the two runs the element had been subjected to the humidity spans and ambient temperatures outlined in Table 1 and to an ambient pressure of 5000 Pa (50 mb). The difference between these two curves may therefore be viewed as the result of the combined effect of aging, testing, cycling, etc. This difference will be defined as long term repeatability. Average and maximum values of long term repeatability are given in Table 8 for the +20 and -40°C isotherms. The long term effect is larger for the experimental type. The +20°C isotherm displays a much larger effect (from two- to three-fold) than the -40°C isotherm. The change that occurs produces both a displacement and a rotation of the isotherm, with the two curves crossing at a high output frequency.

For each element, at each ambient temperature, the calibration data were fitted by the method of least squares to a polynomial equation of the form

$$t = \sum_{i=0}^{n} a_i f^i,$$

where t is the temperature in C of the frost point (below 0°C) and the dew point (above 0°C) and f is the sensor output frequency readings in hertz. Satisfactory fits generally were obtained for n = 3. Higher degree polynomials yielded no significant improvement in the fits. The estimated residual standard deviation σ_r was calculated for each equation using the formula given by Natrella [27]

$$\sigma_r = \left(\frac{\sum_{i=1}^{k} r_i^2}{k-j} \right)^{1/2}$$

where r_i is the difference between the experimental frost (or dew) point and the corresponding computed value, k is the number of fitted points, k-j is the number of degrees of freedom and j is the number of coefficients in the polynomial equation. The residual standard deviation will be used as a measure of estimated random uncertainty arising from the use of the element at the appropriate ambient temperature.

Table 9 gives the values of σ_r for the initial runs. There appears to be a tendency for the residual standard deviation to be larger for the standard type of sensor, except for the 20°C isotherm. At -40°C the mean σ_r for the standard type is 2 times larger than for the experimental type over the -41 to -68°C frost point range and 3 times larger over the -41 to -100°C frost point range. No data were obtained at frost points below -53°C at the ambient temperatures of 20, 0, and -20°C. Therefore, it is not known whether frost points below -53°C would increase the σ_r of these isotherms as it did for the -40°C isotherm. The overall mean σ_r for the five isotherms is 1.5 and 1.3 deg C, respectively for the standard and experimental types of sensor.

The final runs only cover two ambient temperatures: +20 and -40°C. Furthermore, as indicated earlier, the -55 to -100°C frost span was not included in the +20°C runs. Therefore, this span was deleted from the initial runs at -40°C and a new σ_r calculated. The residual standard deviations for the ensuing initial and final runs are compared in Table 10. The values of σ_r for the final runs tend to be larger than for the initial runs.

The hysteresis observed in the elements during the final runs was larger in magnitude than in the initial runs. Table 11 summarizes the average and maximum hysteresis encountered during the final runs.

The typical effect of a change in ambient pressure on the -40°C isotherm is shown in Fig. 8, over the frost-point range of -55 to -90°C. There appears to be no significant difference between the standard atmospheric pressure curve and the 5000 Pa (50 mb) curve for frost points of -55 to -75°C. At -90°C the 50 mb curve dips substantially below the standard atmospheric pressure curve producing an apparent difference in frost point of approximately 3 to 7 deg C. However this observed difference may be due, in part or entirely, to reasons other than ambient pressure. The atmospheric pressure curve represents data taken in the increasing humidity direction, whereas the 50 mb curve represents data taken in the decreasing humidity direction. Thus hysteresis may be a contributing factor. The exposure time for a change from a frost point of -100 to -90°C (at atmospheric pressure) was 7 days; for a change from a frost point of -75 to -90°C (at 50 mb) the exposure time was 3 days. Although it was assumed after these exposure times that steady state conditions were reached because of the almost negligible residual drift in the elements, it is possible that further changes in reading would have occurred with longer exposure times. If steady state conditions were not obtained then the indicated output frequency for the atmospheric pressure curve is too high (since the frequency change was from a higher to lower value) and the indicated output frequency for the 50 mb curve is too low (since the frequency change was from a lower to a higher value).

5. Conclusions and Discussion

Several basic differences between the standard and experimental types of sensor emerge from these tests. The experimental type has greater range and sensitivity. It has larger temperature coefficients. The isotherms for the standard type tend to coalesce at the low frost points (high frequencies) and diverge at the high frost (dew) points (low frequencies). The reverse occurs with the isotherms of the experimental type. The two types perform alike with respect to such characteristics as hysteresis, short term repeatability, long term repeatability, pressure effect, and estimated overall uncertainty.

The individual sensors differ from each other in all major respects and individual calibrations are required.

At ambient temperatures of -40 and -60°C the sensor is capable of detecting frost points as low as -100°C. Tests were not made at higher ambient temperatures so it is not known whether there is a similar capability at higher ambient temperature.

The sensor displays hysteresis. It also undergoes a shift in reading on being subjected to the same monotonic short span of humidity after an elapsed time of 1 to 2 days (short term repeatability). It undergoes a larger shift in calibration after an elapsed time of 5 months (long term repeatability).

The overall mean residual standard deviation σ_r in terms of dew or frost point for the five isotherms comprising the initial run for all standard elements is 1.5 deg C and for all experimental elements is 1.3 deg C. A reasonable estimate for the overall maximum uncertainty inherent in this sensor can therefore be taken as 3 σ_r or 4.5 and 3.9 deg C for the two types of sensors, respectively. There is also a shift in calibration with time or use or both. After subjecting the sensor over a period of five months to a range of ambient temperatures of 20 to -60°C and to frost points as low as -100°C and to ambient pressures of 50 mb, the 20°C isotherm undergoes an average shift of 5.1 and 6.0 deg C in dew or frost point and a maximum shift of 8.5 and 12.1 deg C for the standard and experimental types, respectively, whereas the -40°C isotherm experiences average shifts of 1.4 and 2.5 deg C and maximum shifts of 2.9 and 4.9 deg C for the standard and experimental types, respectively.

It should be emphasized that the conclusions given here are based on data taken on elements that were not exposed to relative humidities above 90 percent. The data presented here indicate that conditions tending to degrade performance, such as aging, hysteresis, etc., tend to have more pronounced effects at the higher humidities. What effect, if any, exposure to conditions of saturation or near saturation would have, is not known. In addition, it is not known how representative these elements are of normal production.

Another important characteristic that was not investigated is the response time (lag). Knowledge of this property is essential for many humidity measurement applications.

A further observation may be worth adding. These tests were made under laboratory conditions where care was taken to minimize or eliminate all known sources of error. If similar precautions are not taken when these (or any other sensors) are utilized for a specific measurement problem, then additional systematic errors may be introduced. For example, in stratospheric measurements using balloon-borne instrumentation such factors as moisture contamination, solar radiation, telemetry errors, shelf life, and lag can contribute large uncertainties.

Table 1

Testing Ranges and Spans

Ambient Temperature, °C				
20	0	-20	-40	-60
Overall testing range in dew/frost point[1], °C				
± 18 to -53	-1 to -53	-21 to -53	-41 to -100	-65 to -100
Testing spans in dew/frost point[1], °C				
+ 18 to -4				
0 to -18	-1 to -19			
-20 to -36	-20 to -36	-21 to -36		
-40 to -53	-40 to -53	-40 to -53	-41 to -53	
			-56 to -68	
			-55 to -100	-65 to -100

[1] Dew point for temperatures above 0°C; frost point for temperature below 0°C.

Table 2

Temperature Coefficient

Frequency	Type of sensor									
	Standard					Experimental				
	Element No.									
	2	4	6	8	9	1	3	5	7	10
hz	Mean temperature coefficient, deg C frost point/deg C ambient temperature									
50	0.15	0.45	0.35	0.55	0.60	0.10	0.20	0.60	0.45	0.25
100	.05	.20	.15	.35	.38	.29	.38	.18	.47	.25
150	.10	.17	.10	.10	.17	.43	.42	.37	.42	.43
200						.52	.45	.38	.40	.52

Table 3

Sensitivity

Type	Element No.	Ambient temperature, °C 20	0	-20	-40	-60	20 to -60
		Average sensitivity, hz/deg C frost point					
Standard	2	2.6	3.0	2.7	1.6	1.0	
	4	1.9	1.9	1.9	0.9	0.6	
	6	2.1	2.3	2.3	1.2	0.7	
	8	2.2	2.4	2.7	1.3	0.7	
	9	2.2	2.4	2.8	1.2	0.6	
	Mean	2.2	2.4	2.5	1.2	0.7	1.8
Experimental	1	3.1	3.2	3.4	2.6	2.4	
	3	3.1	3.5	3.7	2.9	3.0	
	5	3.4	3.7	3.9	2.9	1.7	
	7	3.2	3.9	5.0	3.2	2.7	
	10	2.9	3.3	2.9	2.9	3.1	
	Mean	3.1	3.5	3.8	2.9	2.6	3.2
		Experimental mean sensitivity/standard mean sensitivity					
		1.4	1.5	1.5	2.4	3.7	1.8

Table 4

Average hysteresis

First Calibration Cycle

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average hysteresis, deg C dew/frost point											
20	-53 to -40	0.2	0.0	0.3	0.1	0.1	0.1	0.3	0.2	0.0	0.4	0.0	0.2
	-36 to -20	0.1	0.2	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0
	-18 to 0	0.6	0.3	0.4	0.3	0.3	0.2	0.3	0.2	0.4	0.4	0.5	0.2
	- 4 to 18	3.8	1.6	2.7	1.5	1.3	2.2	1.4	2.7	2.8	3.4	3.6	2.8
0	-53 to -40	0.1	0.2	0.1	0.1	0.2	0.1	0.4	0.3	0.7	0.6	0.1	0.4
	-36 to -20	0.2	0.0	0.3	0.0	0.1	0. 1	0.1	0.0	0.1	0.1	0.1	0.1
	-19 to - 1	2.9	2.7	2.8	2.0	2.2	2.5	1.5	1.7	0.2	1.7	2.3	1.9
-20	-53 to -40	0.2	0.6	0.1	0.0	0.2	0.2	0.2	0.2	0.4	0.2	0.4	0.3
	-36 to -21	1.0	1.1	1.1	0.8	0.9	1.0	1.1	1.0	1.1	0.8	0.8	1.0
-40	-68 to -56	0.2	0.0	0.3	0.0	0.0	0.1	0.0	0.4	1.0	0.4	0.2	0.4
	-53 to -41	0.3	1.4	0.7	0.8	0.6	0.8	1.0	0.4	1.2	1.0	0.2	0.8

Table 5

Maximum hysteresis

First Calibration Cycle

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of Sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Maximum hysteresis, deg C dew/frost point											
20	-53 to -40	0.4	0.0	0.8	0.5	0.6	0.5	0.5	0.4	0.0	0.6	0.0	0.3
	-36 to -20	0.3	0.4	0.2	0.3	0.0	0.2	0.0	0.0	0.0	0.2	0.2	0.1
	-18 to 0	0.7	0.4	0.6	0.4	0.4	0.5	0.6	0.3	0.5	0.5	1.0	0.6
	- 4 to 18	4.6	3.4	3.7	3.2	2.2	3.4	2.4	4.5	4.6	4.7	5.5	4.3
0	-53 to -40	0.2	0.7	0.7	0.3	0.8	0.5	0.6	0.4	1.0	0.7	0.1	0.6
	-36 to -20	0.3	0.0	0.5	0.0	0.4	0.2	0.1	0.0	0.3	0.2	0.2	0.2
	-19 to - 1	3.5	3.5	3.4	2.4	2.9	3.2	2.3	2.8	3.6	3.4	3.1	3.0
-20	-53 to -40	0.3	0.8	0.3	0.0	0.4	0.4	0.3	0.2	0.6	0.3	0.1	0.3
	-36 to -21	1.6	1.9	1.4	1.0	1.2	1.4	1.5	1.3	1.2	1.4	1.0	1.3
-40	-68 to -56	0.3	0.0	0.4	0.0	0.0	0.1	0.0	0.5	1.6	0.7	0.3	0.6
	-53 to -41	0.5	2.2	0.9	1.1	0.8	1.1	1.4	0.7	1.6	1.3	0.3	1.1

Table 6

Average short term repeatability

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average short term repeatability, deg C dew/frost point											
20	-53 to -40	0.5	0.9	0.4	0.8	0.8	0.7	0.7	0.5	0.4	0.5	0.7	0.6
	-36 to -20	0.5	0.7	0.7	0.5	0.4	0.6	0.3	0.4	0.4	0.3	0.4	0.4
	-18 to 0	0.3	0.3	0.8	0.4	0.2	0.4	0.4	0.2	0.1	0.2	0.2	0.2
	- 4 to 18	2.1	1.6	0.9	1.4	0.7	1.5	0.4	1.8	2.0	2.2	2.6	1.8
0	-53 to -40	0.4	0.7	0.8	0.5	0.8	0.6	0.5	0.3	0.4	0.4	0.5	0.4
	-36 to -20	0.4	0.5	0.5	0.4	0.6	0.5	0.2	0.2	0.3	0.2	0.4	0.5
	-19 to - 1	2.2	1.8	2.3	1.4	1.5	1.8	0.8	1.1	1.5	1.1	1.8	1.5
-20	-53 to -40	0.4	0.7	0.6	0.5	0.7	0.6	0.5	0.4	0.5	0.4	0.4	0.4
	-36 to -21	0.6	0.3	0.5	0.3	0.4	0.4	0.3	0.2	0.4	0.3	0.4	0.5
-40	-68 to -56	0.4	0.0	0.2	0.0	0.3	0.2	0.4	0.2	0.6	0.2	0.4	0.4
	-53 to -41	0.2	0.3	0.3	0.4	0.4	0.5	0.2	0.2	0.3	0.2	0.2	0.2

Table 7

Maximum short term repeatability

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Maximum short term repeatability, deg C dew/frost point											
20	-53 to -40	0.7	1.0	0.8	0.9	1.0	0.9	0.8	0.7	0.5	0.7	1.2	0.8
	-36 to -20	0.8	0.8	0.8	0.6	0.4	0.6	0.4	0.6	0.6	0.5	0.5	0.5
	-18 to 0	0.6	0.5	1.0	0.6	0.4	0.6	0.9	0.4	0.3	0.3	0.5	0.5
	- 4 to 18	3.5	5.2	1.4	4.8	3.1	3.6	0.7	3.0	3.3	3.1	4.2	2.9
0	-53 to -40	0.5	0.9	0.9	0.7	0.9	0.8	0.7	0.4	0.6	0.9	0.6	0.6
	-36 to -20	0.8	0.7	0.8	0.8	0.6	0.7	0.3	0.4	0.5	0.3	0.6	0.4
	-19 to - 1	2.7	2.4	2.7	1.7	1.9	2.3	1.3	2.0	2.5	2.3	2.8	2.2
-20	-53 to -40	0.6	1.4	1.1	0.6	0.8	0.9	0.7	0.5	0.6	0.7	0.4	0.6
	-36 to -21	1.3	0.8	1.0	0.5	0.7	0.9	0.4	0.3	0.5	0.4	0.5	0.4
-40	-68 to -56	0.6	0.0	0.5	0.0	0.4	0.3	0.6	0.3	1.2	0.4	0.5	0.6
	-53 to -40	0.4	0.6	0.5	0.6	0.6	0.5	0.7	0.7	0.9	0.4	0.3	0.6

Table 8

Long term repeatability

Comparison of initial and final runs

Type	Element No.	Ambient Temperature, °C			
		20	20	-40	-40
		Long term repeatability, frost point deg C			
		Average	Maximum	Average	Maximum
Standard	2	5.0	8.6	1.6	2.1
	4	5.0	8.5	2.7	4.4
	6	4.6	7.1	1.8	4.9
	8	5.6	8.6	0.5	1.7
	9	5.4	9.7	0.5	1.7
	Mean	5.1	8.5	1.4	3.0
Experimental	1	8.6	15.8	2.5	6.7
	3	5.8	10.7	3.0	6.5
	5	5.2	12.4	3.0	4.0
	7	4.8	10.7	3.5	6.7
	10	5.7	10.7	0.4	0.8
	Mean	6.0	12.1	2.5	4.9

Table 9

Residual standard deviations

Initial runs

Type	Element No.	Ambient temperature, °C						
		20	0	-20	-40 (1)	-40 (2)	-60	20 to -60
		Residual standard deviation, deg C						
Standard	2	1.5	1.2	0.5	0.6	2.9	0.7	
	4	1.3	1.1	0.7	1.9	4.1	0.8	
	6	1.3	1.2	0.5	1.0	3.3	0.4	
	8	1.4	1.0	0.9	1.3	2.5	1.1	
	9	1.4	1.0	0.9	1.2	3.2	1.3	
	Mean	1.4	1.1	0.7	1.2	3.2	0.9	1.5
Experimental	1	1.1	1.0	0.4	0.4	1.1	0.6	
	3	1.2	0.7	0.5	0.4	1.2	0.1	
	5	1.9	1.0	0.2	1.1	1.1	1.0	
	7	1.4	0.9	0.5	0.5	0.8	1.4	
	10	2.3	1.1	0.5	0.4	0.9	0.4	
	Mean	1.6	0.9	0.4	0.6	1.0	0.7	1.3

(1) Based on two frost-point spans: -41 to -53°C and -56 to -68°C.

(2) Based on three frost-point spans: -41 to -53°C, -56 to 68°C, and -55 to -100°C.

Table 10

Residual standard deviations

Comparison of initial and final runs

Type	Element No.	Ambient temperature, °C			
		20	20	-40 (1)	-40 (1)
		Initial	Final	Initial	Final
		Residual standard deviation, deg C			
Standard	2	1.5	2.0	0.6	0.5
	4	1.3	1.6	1.9	0.7
	6	1.3	1.8	1.0	1.1
	8	1.4	2.1	1.3	1.3
	9	1.4	2.0	1.2	1.5
	Mean	1.4	1.9	1.2	1.0
Experimental	1	1.1	1.9	0.4	1.0
	3	1.2	1.8	0.4	0.9
	5	1.9	2.1	1.1	3.1
	7	1.4	1.9	0.5	2.0
	10	2.3	2.0	0.4	-
	Mean	1.6	1.9	0.6	1.7

(1) Based on two frost-point spans: -41 to -53°C and -56 to -68°C.

Table 11

Hysteresis

Final calibration runs

Ambient Temperature °C	Dew/Frost Point Span °C	Standard						Experimental					
		Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average hysteresis, deg C dew/frost point											
20	-53 to -40	0.7	1.7	0.1	1.6	1.1	1.0	0.3	0.5	0.8	0.5	0.2	0.5
	-36 to -20	0.2	0.5	0.5	0.5	0.5	0.4	0.2	0.3	0.3	0.4	0.2	0.3
	-18 to 0	1.5	1.6	1.4	0.9	1.0	1.3	0.8	0.9	0.8	0.7	1.4	0.9
	- 4 to 18	6.0	3.7	4.8	3.1	3.7	4.3	4.2	4.2	4.3	4.4	6.7	4.8
-40	-68 to -56	1.1	0.8	0.8	1.8	1.7	1.2	1.3	1.2	5.9	4.0	-	3.1
	-53 to -41	0.3	0.8	1.4	1.1	1.3	1.0	0.5	0.7	2.8	2.4	-	2.1
		Maximum hysteresis, deg C dew/frost point											
20	-53 to -40	0.7	6.3	1.1	5.5	5.4	3.8	4.0	2.4	4.8	3.0	0.8	3.0
	-36 to -20	0.2	2.2	2.2	1.6	1.6	1.6	0.4	1.0	0.5	0.9	0.8	0.7
	-18 to 0	1.5	2.2	1.9	1.1	1.4	1.6	1.2	1.3	1.1	1.1	1.8	1.3
	- 4 to 18	8.4	6.0	7.1	4.5	6.7	6.5	5.8	7.1	6.6	5.4	10.0	7.0
-40	-68 to -56	1.8	1.8	1.5	3.9	3.4	2.5	2.5	2.2	9.4	5.8	-	5.0
	-53 to -41	0.5	1.4	2.1	1.3	1.9	1.4	2.4	2.2	4.0	3.1	-	2.9

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A laboratory study was made of the performance of aluminum oxide humidity sensors over a range of ambient temperatures from +20°C to -60°C encompassing dew points from +18°C to frost points of -100°C. Information was obtained on such characteristics as sensitivity, hysteresis, temperature effect, pressure-altitude effect and short-term and long-term repeatability. The sensors were found to be capable of detecting frost points as low as -100°C at ambient temperatures of -40°C and -60°C. It is estimated that the total uncertainty inherent in these sensors is approximately 4°C.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Aluminum oxide sensor; humidity; humidity sensor; hygrometer; measurement of frost points; moisture measurement; water vapor measurement.

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